



PATENT APPLICATION

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

In re the application of:

Ian Jordison et al.

Attorney Docket No.: K315.129.101

Application No.: 10/623,207

Examiner: *Unknown*

Filed: July 18, 2003

Group Art Unit: *Unknown*

For: Control of a Switched Reluctance Drive

SUBMISSION OF PRIORITY DOCUMENTS

Commissioner for Patents  
P.O. Box 1450  
Alexandria, VA 22313-1450

Sir:

Applicant claims priority under 35 U.S.C. §119 to British Patent Application Nos. GB 0229841.2, filed December 20, 2002 and GB 0216990.2, filed July 22, 2002. A certified copy of each priority document is enclosed.

It is requested that the file of this application be marked to indicate that the requirements of 35 U.S.C. §119 have been fulfilled, and that the Patent and Trademark Office kindly acknowledge receipt of these documents.

Customer No. 025281  
Dicke, Billig & Czaja, PLLC  
Suite 2250  
100 South Fifth Street  
Minneapolis, Minnesota 55402  
Telephone: (612) 573-2010

Respectfully submitted,

William M. Hienz III  
Registration No. 37,069

*Please grant any extension of time necessary for entry; charge any fee due to Deposit Account No. 500471.*

CERTIFICATE UNDER 37 C.F.R. 1.8:

The undersigned hereby certifies that this paper or papers, as described herein, are being deposited in the United States Postal Service, as first class mail with sufficient postage, in an envelope addressed to Commissioner for Patents, P.O. Box 1450, Alexandria, VA 22313-1450 on this 7<sup>th</sup> day of August, 2003.

By   
Name: William M. Hienz III



INVESTOR IN PEOPLE

The Patent Office  
Concept House  
Cardiff Road  
Newport  
South Wales  
NP10 8QQ

I, the undersigned, being an officer duly authorised in accordance with Section 74(1) and (4) of the Deregulation & Contracting Out Act 1994, to sign and issue certificates on behalf of the Comptroller-General, hereby certify that annexed hereto is a true copy of the documents as originally filed in connection with the patent application identified therein.

In accordance with the Patents (Companies Re-registration) Rules 1982, if a company named in this certificate and any accompanying documents has re-registered under the Companies Act 1980 with the same name as that with which it was registered immediately before re-registration save for the substitution as, or inclusion as, the last part of the name of the words "public limited company" or their equivalents in Welsh, references to the name of the company in this certificate and any accompanying documents shall be treated as references to the name with which it is so re-registered.

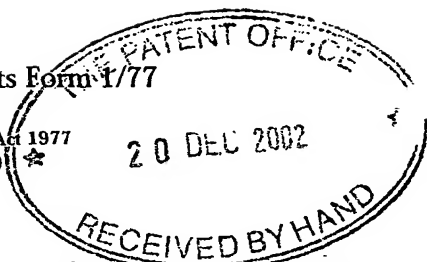
In accordance with the rules, the words "public limited company" may be replaced by p.l.c., plc, P.L.C. or PLC.

Re-registration under the Companies Act does not constitute a new legal entity but merely subjects the company to certain additional company law rules.



Signed

Dated 11 July 2003



# Request for grant of a patent

(See the notes on the back of this form. You can also get an explanatory leaflet from the Patent Office to help you fill in this form)

The Patent Office

Cardiff Road  
Newport  
South Wales  
NP9 1RH

1. Your reference P35042GB/JJH

2. Patent application number  
(The Patent Office will fill in this part)

0229841.2

20 DEC 2002

3. Full name, address and postcode of the or of each applicant (underline all surnames)

Switched Reluctance Drives Limited  
East Park House, Otley Road  
Harrogate, HG3 1PR

Patents ADP number (if you know it)

If the applicant is a corporate body, give the country/state of its incorporation

United Kingdom

07 01 07 13001

4. Title of the invention

Angle/Time Control for a Generator

5. Name of your agent (if you have one)

"Address for service" in the United Kingdom to which all correspondence should be sent (including the postcode)

Kilburn & Strode  
20 Red Lion Street  
London  
WC1R 4PJ

Patents ADP number (if you know it)

125001

6. If you are declaring priority from one or more earlier patent applications, give the country and the date of filing of the or of each of these earlier applications and (if you know it) the or each application number

Country

Priority application number  
(if you know it)

Date of filing  
(day / month / year)

7. If this application is divided or otherwise derived from an earlier UK application, give the number and the filing date of the earlier application

Number of earlier application

Date of filing  
(day / month / year)

8. Is a statement of inventorship and of right to grant of a patent required in support of this request? (Answer 'Yes' if:

- a) any applicant named in part 3 is not an inventor, or
  - b) there is an inventor who is not named as an applicant, or
  - c) any named applicant is a corporate body.
- See note (d))

YES

## Patents Form 1/77

9. Enter the number of sheets for any of the following items you are filing with this form.  
Do not count copies of the same document

Continuation sheets of this form

Description 14

Claim(s) 4

Abstract 1

Drawing(s) 5 + 5 *SW*

10. If you are also filing any of the following, state how many against each item.

Priority documents

Translations of priority documents

Statement of inventorship and right to grant of a patent (*Patents Form 7/77*)

Request for preliminary examination and search (*Patents Form 9/77*)

Request for substantive examination (*Patents Form 10/77*)

Any other documents  
(please specify)

11. I/We request the grant of a patent on the basis of this application.

Signature

*Juliet Hibbert*

Date 20/12/02

12. Name and daytime telephone number of person to contact in the United Kingdom

Hibbert, Juliet Jane Grace  
Tel: 020 7539 4200

### Warning

*After an application for a patent has been filed, the Comptroller of the Patent Office will consider whether publication or communication of the invention should be prohibited or restricted under Section 22 of the Patents Act 1977. You will be informed if it is necessary to prohibit or restrict your invention in this way. Furthermore, if you live in the United Kingdom, Section 23 of the Patents Act 1977 stops you from applying for a patent abroad without first getting written permission from the Patent Office unless an application has been filed at least 6 weeks beforehand in the United Kingdom for a patent for the same invention and either no direction prohibiting publication or communication has been given, or any such direction has been revoked.*

### Notes

- If you need help to fill in this form or you have any questions, please contact the Patent Office on 0645 500505.*
- Write your answers in capital letters using black ink or you may type them.*
- If there is not enough space for all the relevant details on any part of this form, please continue on a separate sheet of paper and write "see continuation sheet" in the relevant part(s). Any continuation sheet should be attached to this form.*
- If you have answered 'Yes' Patents Form 7/77 will need to be filed.*
- Once you have filled in the form you must remember to sign and date it.*
- For details of the fee and ways to pay please contact the Patent Office.*

## **Control of a Switched Reluctance Drive**

This invention relates to the control of reluctance machines, particularly of switched reluctance machines.

5

The control and operation of switched reluctance machines generally are described in the paper "The Characteristics, Design and Applications of Switched Reluctance Motors and Drives" by J. M. Stephenson and R. J. Blake delivered at the PCIM'93 Conference and Exhibition held in Nurnberg, Germany, 21-24 June 1993 and incorporated herein by reference. In that paper "chopping" and "single-pulse" modes of energisation of switched reluctance machines are described for operation of the machine at low and high speeds respectively.

15 A typical prior art drive is shown schematically in Figure 1. This includes a DC power supply 11 that can be either a battery or rectified and filtered AC mains. The DC voltage provided by the power supply 11 is switched across phase windings 16 of the motor 12 by a power converter 13 under the control of the electronic control unit 14. Some form of current transducer 18 is  
20 normally provided to give phase current feedback. One of the many known converter topologies is shown in Figure 2, where a resistor 28 is connected in series with the lower switch 22 to provide a current feedback signal.

25 The performance of a switched reluctance machine depends, in part, on the accurate timing of phase energisation with respect to rotor position. Detection of rotor position is conventionally achieved by using a transducer 15, shown schematically in Figure 1, such as a rotating toothed disk mounted on the machine rotor, which co-operates with an optical or magnetic sensor mounted on the stator. A pulse train indicative of rotor position relative to the stator is

generated and supplied to control circuitry, allowing accurate phase energisation. Alternative methods of position detection include the so-called “sensorless” methods, in which the position is deduced from measurements of another parameter of the machine.

5

At low speeds, switched reluctance systems generally operate in a current-controlled or “chopping” mode, as illustrated generally in Figure 3 for motoring. A hysteresis current controller using “hard” chopping is often used, as shown in Figure 3(a). Typically, the voltage is applied to the phase at an angle  $\theta_{on}$  in the minimum inductance region and the current rises rapidly till an upper bound  $I_u$  is reached, whereupon the switches are opened and the full reverse voltage is applied across the winding by the action of the diodes 23,24, driving down the flux and hence the current. When a lower bound  $I_l$  is reached, the switches are then closed and the current rises again. The cycle is repeated until the switch-off angle  $\theta_{off}$  is reached, typically at the point of maximum inductance when the rotor poles are fully aligned with the stator poles. The current is then forced down to zero by the reverse voltage. The current remains at zero until the cycle begins again at  $\theta_{on}$ , so the mark:space ratio of the current is approximately 0.5.

20

An alternative regime, known as “soft” chopping, is illustrated in Figure 3(b) in which only one switch is opened when the current reaches its upper bound, the current then decaying much more slowly through the winding, the second switch and one diode. The resulting reduction in switching frequency is often beneficial in reducing switching loss in the switches and reducing acoustic noise. Other types of current controllers are well known in the art, for example off-time controllers, constant frequency controllers, etc., and will not be described here. Their common characteristic, however, is that they all limit the current to a safe level to prevent damage to the switches and/or the machine.

25

At higher speeds, switched reluctance systems typically operate in the "single-pulse" mode of energisation. This mode is illustrated in Figure 4 in which the current and linearised inductance waveforms are shown over a phase inductance period. The current rises when the voltage is applied to the phase winding at the switch-on angle  $\theta_{on}$ , reaches a peak and then rolls over as the rotor poles begin to overlap the stator poles and the inductance rises. The current is limited naturally by the back emf of the circuit. The voltage is reversed at  $\theta_{off}$  and the current falls at a faster rate as energy is returned to the supply and ceases when it reaches zero. There is then a period of zero current before the cycle begins again.

An alternative switching strategy uses freewheeling for a period  $\theta_f$  before  $\theta_{off}$ , whereby the switching circuit allows the current to re-circulate in the phase winding without an applied voltage. Figure 5 illustrates this technique and the period of zero applied voltage during freewheeling is clearly shown. Again, the current falls to zero for a time before the cycle repeats.

Thus systems generally use a chopping mode at low speeds and a single-pulse mode at higher speeds. The parameters  $I_u$  and  $I_l$  (used in the chopping mode) are normally set to values above the expected peak current of the single pulse mode, so that these parameters do not interfere with single-pulse operation. It is known to set the parameter  $I_u$  to a value which would act as a "safety net" so that if a fault condition developed in the drive the excess current would exceed  $I_u$  and cause the drive to switch off.

A special mode of operation of switched reluctance machines is the continuous current mode, as disclosed in US Patent No. 5469039 (Stephenson) and incorporated herein by reference. In this mode, the winding is re-connected to

the supply before the flux, and hence the current, have returned to zero at the end of the energy return period. The phase windings therefore operate with current continuously flowing through them and are always linked by flux. Although previously considered to be so unstable as to be unusable, US  
 5 5469039 discloses a method of operating in a stable manner in this region so that steady state operation is possible. Figure 6 shows a steady-state current waveform in motoring, where the current variation is quasi-sinusoidal above a "standing" value  $I_s$ . This is an important mode for systems which have to produce high levels of overload output at some points of their operating cycle.  
 10 Although the efficiency of the drive falls in this mode, it allows specifications to be achieved which would otherwise require a larger machine.

While motoring operation has been illustrated in the above discussions, it is well-known that the machines operate equally well in the generating mode, in  
 15 which the current waveforms are generally mirror images of the motoring waveforms.

The parameters of  $\theta_{on}$ ,  $\theta_{off}$ ,  $I_u$ ,  $I_l$ ,  $\theta_f$ , etc., are generally functions of speed and are either computed in real time or, more commonly, stored in some form of  
 20 table from which they can be read at appropriate times. The parameter values are carefully chosen in order to achieve smooth output from the machine as the speed changes. If the stored values are relatively sparse, some form of interpolation is used to give suitable parameter values at intermediate speeds. There is a particular difficulty in choosing values at the transition points  
 25 between chopping and single-pulse modes, and between single-pulse and continuous current modes, where a smooth transition is desired regardless of the torque level demanded.



One solution to this problem at the transition of the chopping and single-pulse modes is to use the current control parameters as the main variable. Whereas the current level is generally held constant with speed for a given torque demand throughout the chopping range, as the speed rises to the single-pulse mode it is known to raise the upper bound  $I_u$  gradually (and sometimes the lower bound  $I_l$  by corresponding amounts) so that the waveform gradually changes from that of, say Figure 3(a) to that of Figure 4. Once the machine has reached a speed where the current never reaches the upper current bound, the current control parameters are generally set to a high value so that they do not come into play for the rest of the speed range.

No such solution is available for the transition from single-pulse to continuous current, and careful selection of parameters is generally relied on to give a smooth transition. It is a feature of the continuous current mode that the sensitivity to angle parameters (particularly to the total conduction angle  $\theta_c$ , which is the angular difference between  $\theta_{on}$  and  $\theta_{off}$ ) is much higher than in single-pulse mode, so small differences in parameter value can produce undesirably large variations in output.

Most variable speed drive systems have to operate over a range of supply voltages and in some cases, (typically those drives operating in remote areas or from an isolated power source), that range is a very significant fraction of the nominal supply voltage. While this is generally not a serious difficulty for switched reluctance systems in the chopping mode (since the current controller is generally capable of coping with the changing current gradients), it becomes a problem in single-pulse and continuous current modes, where the torque is strongly dependent on the supply voltage. Known attempts to solve this problem include the storing of a complete set of control parameters for a range of supply voltages (i.e. introducing a further parameter, supply voltage, into the

set), but this often creates unacceptable demands on storage space in the controller.

In single-pulse mode, methods of voltage compensation have been developed which cope with this variation of supply voltage. For example, US Patent No. 5724477 (Webster), incorporated herein by reference, discloses a method of modifying the speed signal so as to arrive at a set of control parameters which efficiently produce the demanded torque. Other methods of voltage compensation are known for use in the single-pulse mode.

In the continuous current mode, however, these methods are seldom satisfactory. If, for example, the machine is operating just above the transition from single-pulse to continuous current and the supply voltage then rises, use of a voltage compensation scheme such as that disclosed in US Patent No. 5724477 is likely to generate control parameters which immediately drop the machine out of continuous current. The developed torque then immediately falls, leading to a drop in speed. If the drive is in speed control, the torque error rapidly rises to compensate, which then generates new control parameters which force the system back into continuous current mode. This sequence produces significant disturbance in the torque output, which can lead to the build up of oscillations and/or other instability.

In the single-pulse mode, the developed torque is largely independent of the winding resistance (except perhaps in the smallest of machines). As the machine experiences changes in load, the winding temperature, and hence winding resistance, changes but the output of the machine is effectively independent, thus allowing the use of control parameters which are unaffected by winding resistance. In continuous current, however, the current is a strong function of the system resistance so, for given control parameters, the output

fluctuates with the thermal state of the winding. Even if reliable thermal feedback from the winding were available at a reasonable cost, providing control parameters which compensated for temperature would place an unacceptable burden on storage in the controller.

5

It is therefore clear that there is a need for a method of voltage compensation for use in the continuous current mode which is able to compensate for varying supply voltage and changes in winding temperature and also give a smooth transition from and to the single-pulse mode.

10

In accordance with a first aspect of the invention there is provided a method of controlling a switched reluctance machine in continuous current mode of operation, the switched reluctance machine comprising a rotor having a plurality of poles, a stator having a plurality of poles and at least one phase winding, the method comprising:

15

generating a first signal when the rotor reaches a first pre-determined position, which first signal causes a voltage to be applied to the phase winding, and

20

generating a second signal when the phase current in the phase winding reaches a first pre-determined level, which second signal causes the phase winding to freewheel, thereby controlling the output of the machine.

25

Thus the phase winding freewheels for at least part of the remainder of the conduction angle of the phase winding. In the motoring mode this tends to control the standing current in the phase winding and in generating mode this tends to control the output voltage of the machine.

The method may also comprise generating a third signal, which third signal causes reversal of the voltage on the phase winding. This third signal may be

generated when the rotor reaches a second pre-determined position or when the phase current in the phase winding reaches a second pre-determined level higher than the first. Alternatively, the third signal may be generated when the first of the following two conditions is met: the rotor reaches a second pre-determined position or the phase current in the phase winding reaches a second pre-determined level higher than the first.

Preferably the first pre-determined level of phase current in the phase winding is set to be below the expected peak current of the phase winding and/or the second pre-determined level of phase current in the phase winding is set to be above the expected peak current of the phase winding.

According to a further aspect of the invention there is provided a control device for use in controlling the operation of a switched reluctance machine comprising a rotor having a plurality of poles, a stator having a plurality of poles and at least one phase winding, the control device comprising:

- an input for receiving an angular position signal from position sensing means, said angular position signal being indicative of the angular position of the rotor with respect to the stator,

- an input for receiving a phase current signal indicative of the current in a phase winding,

- an output to output a control signal to a switching arrangement, and

- a processor arranged to monitor the signals received at the inputs and to generate the control signal,

- wherein the processor is arranged to

- generate a first control signal when the angular position signal indicates that the rotor is at a first pre-determined position, which first signal causes a voltage to be applied to the phase winding, and

generate a second control signal when the phase current signal indicates that current in the phase winding is at a first pre-determined level, which second signal causes the phase winding to freewheel, thereby controlling the standing current in the phase winding.

5

Preferably the processor is further arranged to generate a third signal, which third signal causes reversal of the voltage on the phase winding. The third signal may be generated when the rotor reaches a second pre-determined position or when the phase current in the phase winding reaches a second pre-determined level higher than the first. Alternatively the processor may be further arranged to generate a third signal, which third signal causes reversal of the voltage on the phase winding, when the first of the following two conditions is met: the rotor reaches a second pre-determined position or the phase current in the phase winding reaches a second pre-determined level higher than the first.

10  
15

Preferably the first pre-determined level of phase current in the phase winding is set to be below the expected peak current of the phase winding and/or the second pre-determined level of phase current in the phase winding is set to be above the expected peak current of the phase winding.

20

According to a third aspect of the invention there is provided a control system for use with a switched reluctance machine comprising a rotor having a plurality of poles, a stator having a plurality of poles and at least one phase winding, the control system comprising:

25

- a switching arrangement,

- position sensing means for generating an angular position signal indicative of the angular position of the rotor with respect to the stator,

a current sensor for generating a phase current signal indicative of the phase current in a phase winding, and

5 a control device, operatively coupled to the switching arrangement, the position sensing means and the current sensor, and arranged to receive the angular position signal and the phase current signal and to output a control signal to the switching arrangement,

wherein the control means is arranged, in a continuous current mode of operation, to generate a first control signal when the angular position signal indicates that the rotor is at a first pre-determined position, which first signal causes a voltage to be applied to the phase winding, and

10 to generate a second control signal to actuate the switching arrangement when the phase current reaches a predetermined threshold and so cause the phase winding to freewheel, thereby controlling the standing current in the phase winding.

15

The invention can be put into practice in a number of ways, some of which will now be described by way of example and with reference to the accompanying drawings in which:

Figure 1 shows a typical prior art switched reluctance drive;

20 Figure 2 shows a known topology of one phase of the converter of Figure 1;

Figure 3(a) and Figure 3(b) show typical chopping control waveforms;

Figure 4 shows a typical current waveform in single-pulse control;

Figure 5 shows a typical current waveform in single-pulse control using freewheeling;

25 Figure 6 shows a typical current waveform in continuous current mode;

Figure 7 shows a current waveform of the machine operating according to one aspect of the invention;

Figure 8 shows a current waveform of the machine operating according to another aspect of the invention;

Figure 9 shows the recovery time of a generator subject to a load dump;

The phase inductance cycle of a switched reluctance machine is the period of the variation of inductance for the, or each, phase; for example the period between maxima when the rotor poles and the relevant respective stator poles are fully aligned. The illustrative embodiments to be described use a 3-phase switched reluctance drive, but any number of phases could be used, with the machine in either motoring or generating mode.

The method of control uses a combination of switch-on angle, switch-off angle and current level to trigger an optional period of freewheeling which controls the standing current,  $I_s$ , in the phase. Unlike previous methods of control in the continuous current mode, this method allows smooth control of the standing value of current with no abrupt dropping out of continuous current.

Figure 7 shows a typical set of control parameters chosen according to the invention. In operation, the phase is switched on at  $\theta_{on}$  in the usual way. A current level  $I_x$  is chosen, the value of which is a little below the natural peak current of the phase. The control system is arranged so that, when the phase current reaches  $I_x$ , the phase is put into freewheel until the switch-off angle  $\theta_{off}$  is reached (i.e. for the remainder of the conduction angle of the phase), at which point the control becomes conventional, with both switches off. Contrary to expectation, this does not make a significant change to either the peak current or the shape of the waveform. Instead, it allows control of the level of standing current: varying  $I_x$  by a small amount gives a corresponding variation in  $I_s$ .

This unexpected result has significant benefits in control. If the supply voltage now increases or the resistance of the winding decreases due to a fall in

temperature, the phase current rises faster and reaches  $I_x$  more quickly, effectively giving a shorter on time and a longer freewheel time, thus preventing an increase in the standing current  $I_s$  and stabilising the system. Conversely, a decrease in supply voltage or an increase in resistance gives a slower rise in current, increasing the on time and decreasing the freewheel time and preventing the standing current falling. It is the combination of angle and current parameters which enable this to be achieved.

There are further benefits with this method of control in that it reduces the requirement for fine resolution of the on- and off-angles. It has previously been held that very fine resolution of these parameters is required for successful control in the continuous current mode, since the sensitivity of output to angle is high in this mode. However, this can be costly to achieve since, for example, the cost of a position resolver is very dependent on its resolution. Indeed, in some systems, the amount of continuous current which can be employed is severely limited by the degree of control available on the angle parameters. This invention, however, allows the use of a current parameter, which is easily controlled with fine resolution, to effectively "fill in" load points between steps in the angle parameters.

A variation of the method is to have two current parameters, as shown in Figure 8. The second parameter,  $I_y$ , is set above  $I_x$  and the expected peak current of the waveform. In operation, if the current rises significantly in freewheeling (i.e. after  $I_x$  has been reached) because, say, generation is taking place, then  $I_y$  can be used to switch off the second switch, effectively advancing the  $\theta_{\text{off}}$  parameter. Thus the phase does not freewheel for all of the remainder of the conduction angle of the phase. The phase freewheels for a fraction of the remainder of the conduction angle of the phase.



When implementing the invention, it is generally advantageous to characterise the machine at nominal voltage and average temperature rise. This allows  $I_x$  to be chosen to accommodate both rise and fall of voltage and temperature. It is also advantageous to characterise the points before the entry to continuous current with  $I_x$  set a little bit above the natural peak current, so that when the voltage rises and the machine would otherwise abruptly enter continuous current, the presence of the current control  $I_x$  will soften the entry and stabilise the system.

10 A further embodiment of the invention will be described, which is particularly useful when the machine is operating in the generating mode. When operating in generating mode, the speed of the machine is generally constant, or at least varies only slowly, since the inertia of the mechanical arrangement is usually dominated by the prime mover. Unless the system is generating onto  
15 a "stiff" supply, the voltage is controlled principally by the electrical load and the size and rating of the dc link capacitor(s) (i.e. capacitor 25 in Figure 2). If there is a sudden change in the electrical load, e.g. the so-called "load dump" situation when at least part of the load is disconnected suddenly, then, unless the control system can react quickly, there will be a corresponding voltage  
20 swing on the dc link. This is undesirable from the point of view of the remaining load(s) and, if it is an upwards voltage swing, of the dc link capacitors, which may fail catastrophically on serious over-voltage. If the machine is operating in chopping or single-pulse mode, the bandwidth of the control system is generally sufficient to control the transient by modifying the  
25 control angles. However, if the machine is operating in continuous current mode, the response is necessarily much slower, since it takes many cycles for the standing current to reach a new steady-state value.

This is illustrated in Figure 9, which shows the voltage output of a switched reluctance generator, rated at 10kW, operating at a speed of 3600 rpm. Before  $t=0$  the generator is supplying 10kW to a load and the voltage is steady at its rated value of 340V. At  $t=0$ , the load is suddenly removed and, under conventional P+I control, the voltage swings up to 428V (i.e. +19%) and takes  
5 around 200 msec to recover. While increasing the gains of the controller may help to reduce these excursions, too high a gain will in itself cause instability.

Applying the invention to this situation by controlling the on-angle and a  
10 current parameter, shows an immediate benefit, as seen in Figure 9, where the overshoot is reduced to 385V and the recovery time reduces to 12msec. It will be appreciated that the energy in the transient has been reduced to around 4% of the previous case, greatly reducing unwanted side effects.

15 It will be appreciated that the same principles apply for the smaller transients caused by smaller changes in load. They also apply to a sudden increase in load, which would lead to a negative swing in the output voltage.

The skilled person will appreciate that variations of the disclosed arrangements  
20 are possible without departing from the invention, particularly in the details of the implementation of the algorithm in the microprocessor. Accordingly, the above description of several embodiments is made by way of example and not for the purposes of limitation. It will be clear to the skilled person that minor modifications can be made to the drive circuit without significant changes to  
25 the operation described above. The present invention is intended to be limited only by the scope of the following claims.

**Claims**

1. A method of controlling a switched reluctance machine in continuous current mode of operation, the switched reluctance machine comprising a rotor having a plurality of poles, a stator having a plurality of poles and at least one phase winding, the method comprising  
5 generating a first signal when the rotor reaches a first pre-determined position, which first signal causes a voltage to be applied to the phase winding, and  
10 generating a second signal when the phase current in the phase winding reaches a first pre-determined level, which second signal causes the phase winding to freewheel, thereby controlling the output of the machine.
2. A method according to claim 1 further comprising  
15 generating a third signal, which third signal causes reversal of the voltage on the phase winding, when the rotor reaches a second pre-determined position.
3. A method according to claim 1 further comprising  
20 generating a third signal, which third signal causes reversal of the voltage on the phase winding, when the phase current in the phase winding reaches a second pre-determined level higher than the first.
4. A method according to claim 1 further comprising  
25 generating a third signal, which third signal causes reversal of the voltage on the phase winding, when the first of the following two conditions is met: the rotor reaches a second pre-determined position or the phase current in the phase winding reaches a second pre-determined level higher than the first.

5. A method according to any preceding claim wherein the first pre-determined level of phase current in the phase winding is set to be below the expected peak current of the phase winding.

5 6. A method according to claim 3, 4 or 5 wherein the second pre-determined level of phase current in the phase winding is set to be above the expected peak current of the phase winding.

7. A control device for use in controlling the operation of a switched reluctance machine comprising a rotor having a plurality of poles, a stator having a plurality of poles and at least one phase winding, the control device comprising:

10 an input for receiving an angular position signal from position sensing means, said angular position signal being indicative of the angular position of the rotor with respect to the stator,

15 an input for receiving a phase current signal indicative of the current in a phase winding,

an output to output a control signal to a switching arrangement, and  
a processor arranged to monitor the signals received at the inputs and to generate the control signal,

20 wherein the processor is arranged to generate a first control signal when the angular position signal indicates that the rotor is at a first pre-determined position, which first signal causes a voltage to be applied to the phase winding, and

25 generate a second control signal when the phase current signal indicates that current in the phase winding is at a first pre-determined level, which second signal causes the phase winding to freewheel, thereby controlling the standing current in the phase winding.

8. A control device according to claim 7 wherein the processor is further arranged to

generate a third signal, which third signal causes reversal of the voltage on the phase winding, when the rotor reaches a second pre-determined position.

5

9. A control device according to claim 7 wherein the processor is further arranged to

generate a third signal, which third signal causes reversal of the voltage on the phase winding, when the phase current in the phase winding reaches a second pre-determined level higher than the first.

10

10. A control device according to claim 7 wherein the processor is further arranged to

generate a third signal, which third signal causes reversal of the voltage on the phase winding, when the first of the following two conditions is met: the rotor reaches a second pre-determined position or the phase current in the phase winding reaches a second pre-determined level higher than the first.

15

11. A control device according to any of claims 7 to 10 wherein the first pre-determined level of phase current in the phase winding is set to be below the expected peak current of the phase winding.

20

12. A control device according to claim 9, 10 or 11 wherein the second pre-determined level of phase current in the phase winding is set to be above the expected peak current of the phase winding.

25

13. A control system for use with a switched reluctance machine comprising a rotor having a plurality of poles, a stator having a plurality of poles and at least one phase winding, the control system comprising:

a switching arrangement,

position sensing means for generating an angular position signal indicative of the angular position of the rotor with respect to the stator,

5 a current sensor for generating a phase current signal indicative of the phase current in a phase winding, and

a control device, operatively coupled to the switching arrangement, the position sensing means and the current sensor, and arranged to receive the angular position signal and the phase current signal and to output a control signal to the switching arrangement,

10 wherein the control means is arranged, in a continuous current mode of operation, to generate a first control signal when the angular position signal indicates that the rotor is at a first pre-determined position, which first signal causes a voltage to be applied to the phase winding, and

15 to generate a second control signal to actuate the switching arrangement when the phase current reaches a predetermined threshold and so cause the phase winding to freewheel, thereby controlling the standing current in the phase winding.

**ABSTRACT**

A switched reluctance drive, operating either as a motor or a generator, is controlled in a stable manner in the continuous current mode in the presence of supply voltage or electrical load variation. The use of a current control parameter  $I_x$  in addition to the conventional on- and off-angles  $\theta_{on}$ ,  $\theta_{off}$  gives the ability to operate smoothly in the continuous current mode and to transition smoothly between operating modes. Once the phase current reaches a predetermined level  $I_x$ , the phase winding may be placed in a freewheel state, thereby controlling the standing current in the phase winding and/or the output voltage.

**Figure 7**

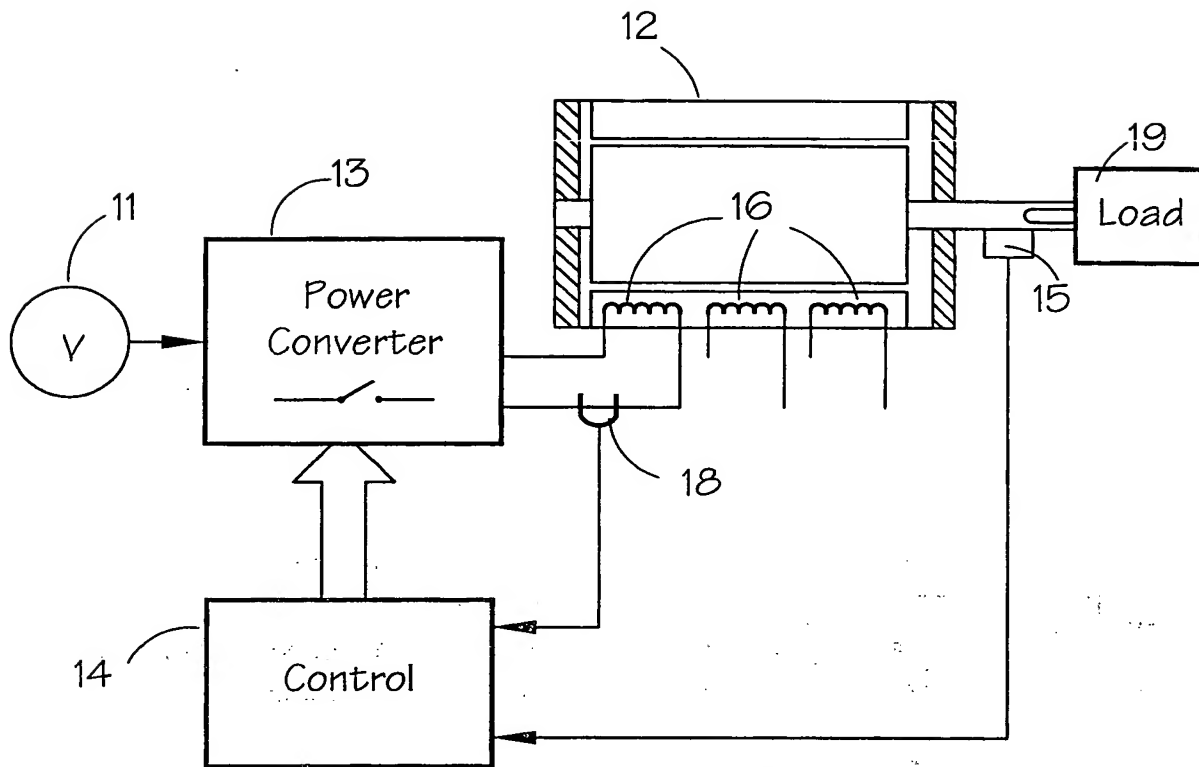


Fig 1 Prior Art

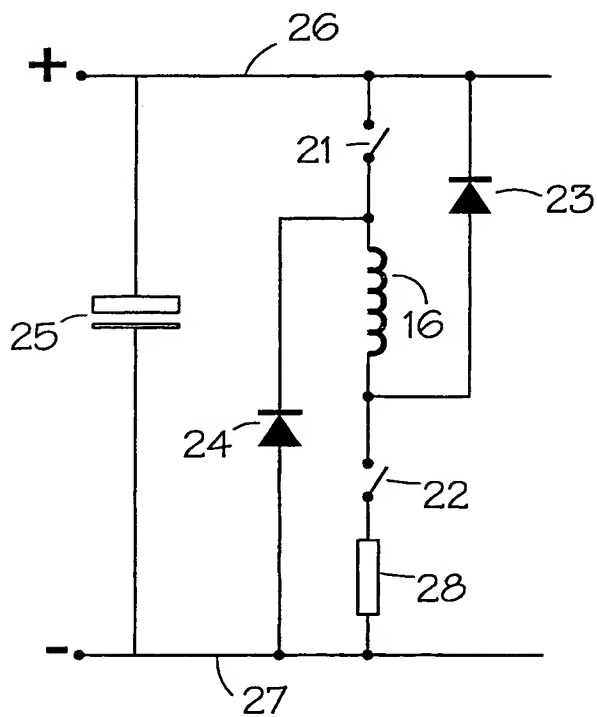


Fig 2  
Prior Art



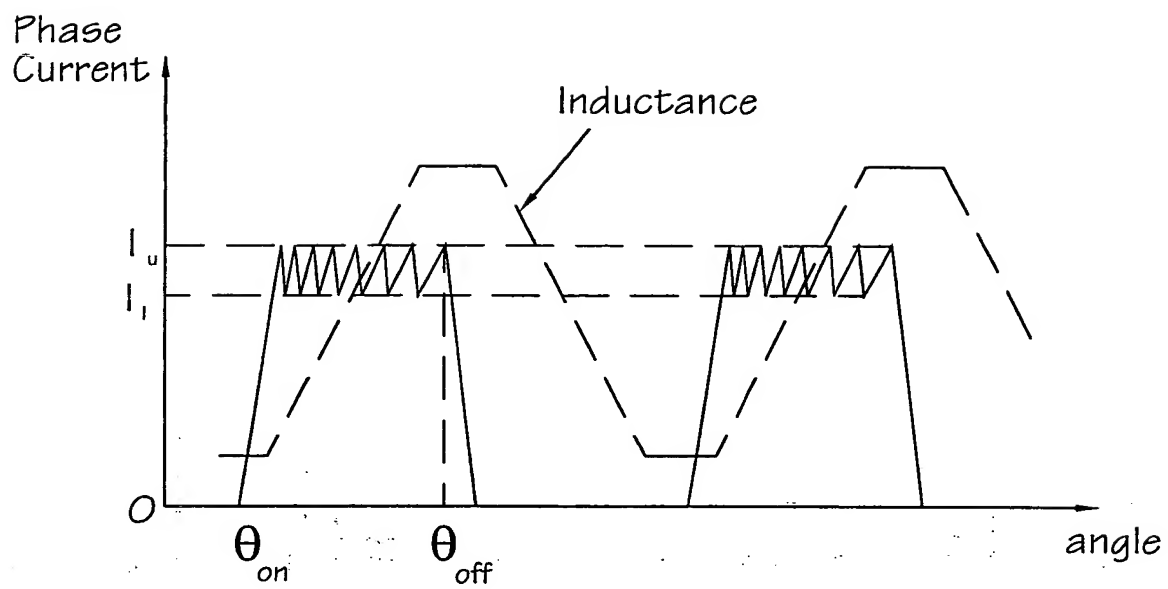


Fig 3(a)  
Prior Art

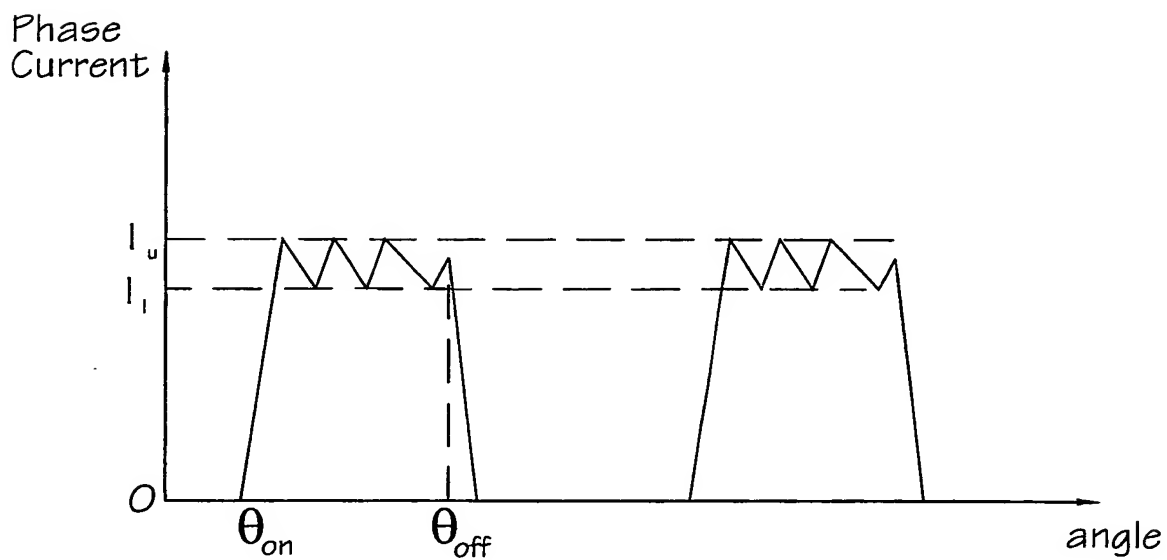


Fig 3(b)  
Prior Art

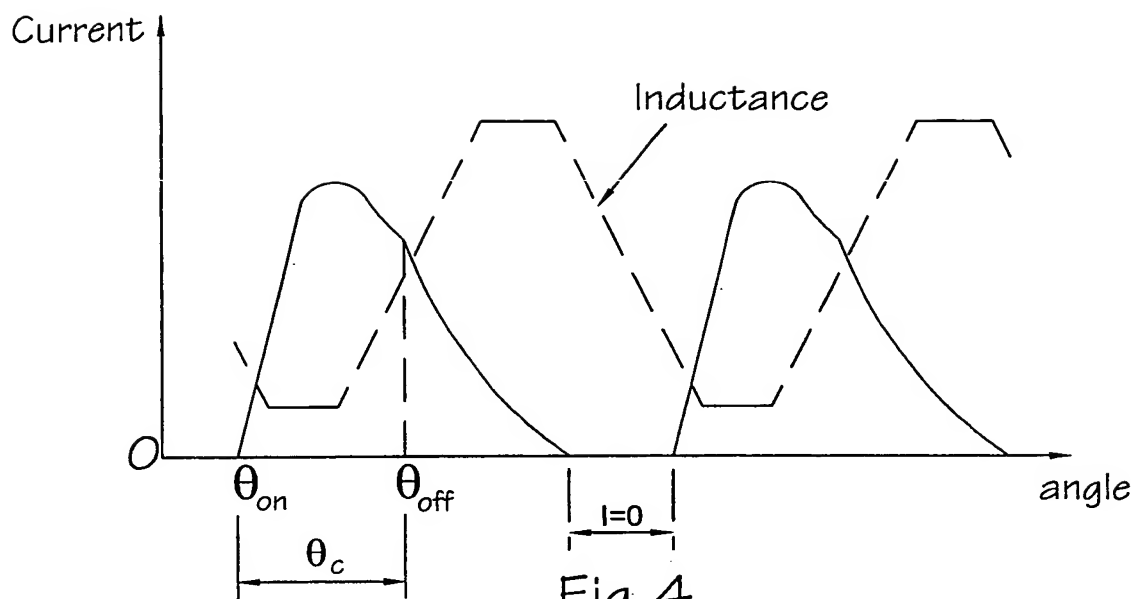


Fig 4  
Prior Art

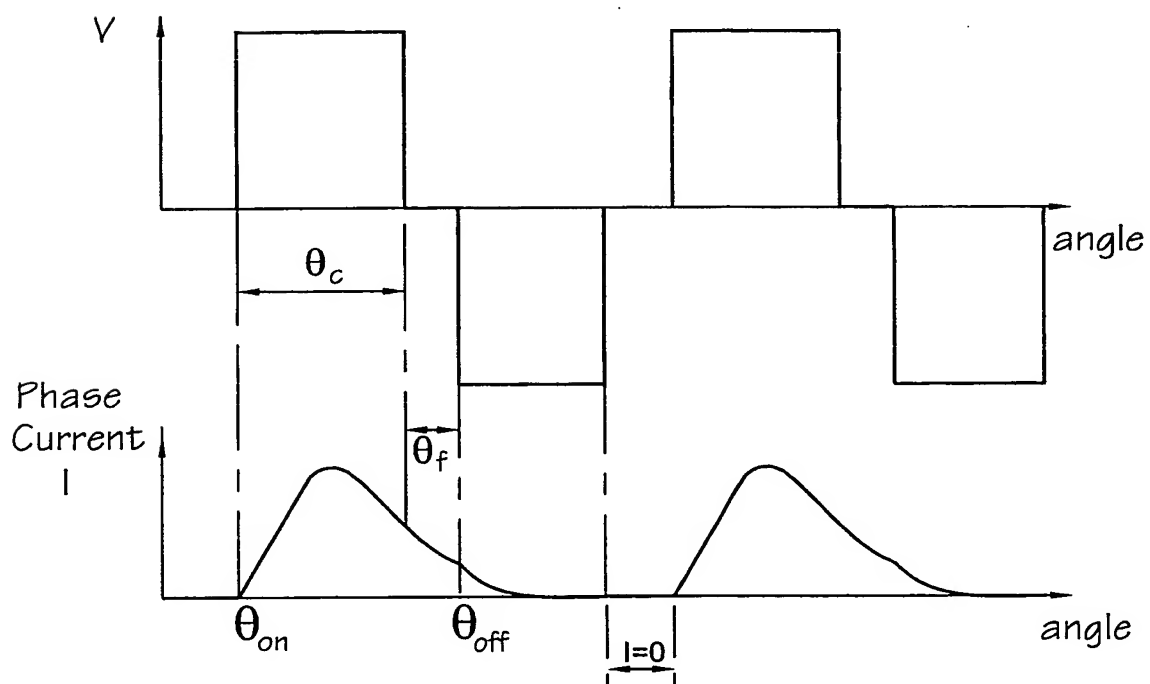


Fig 5  
Prior Art

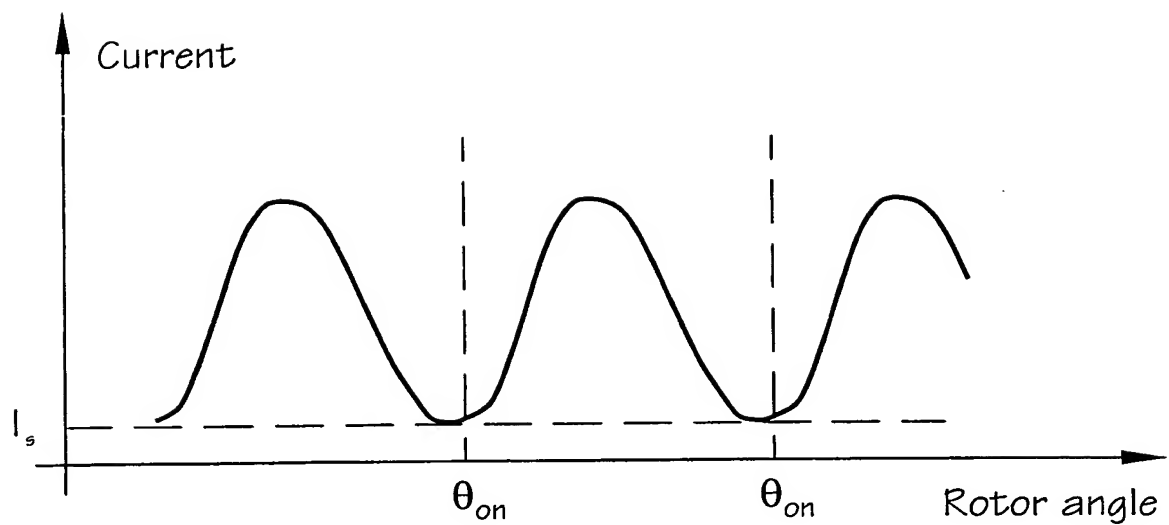


Fig 6  
Prior Art

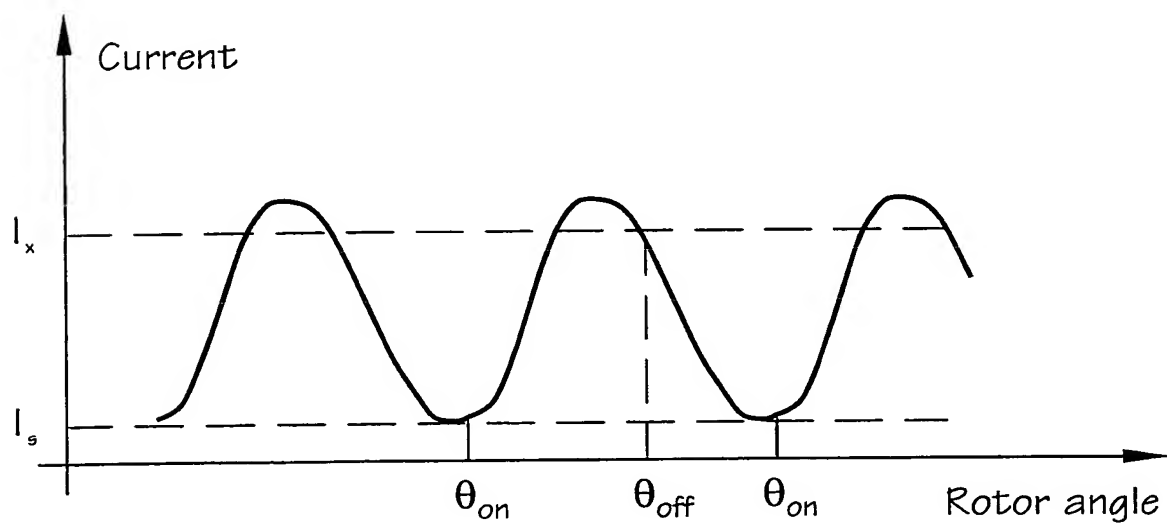


Fig 7

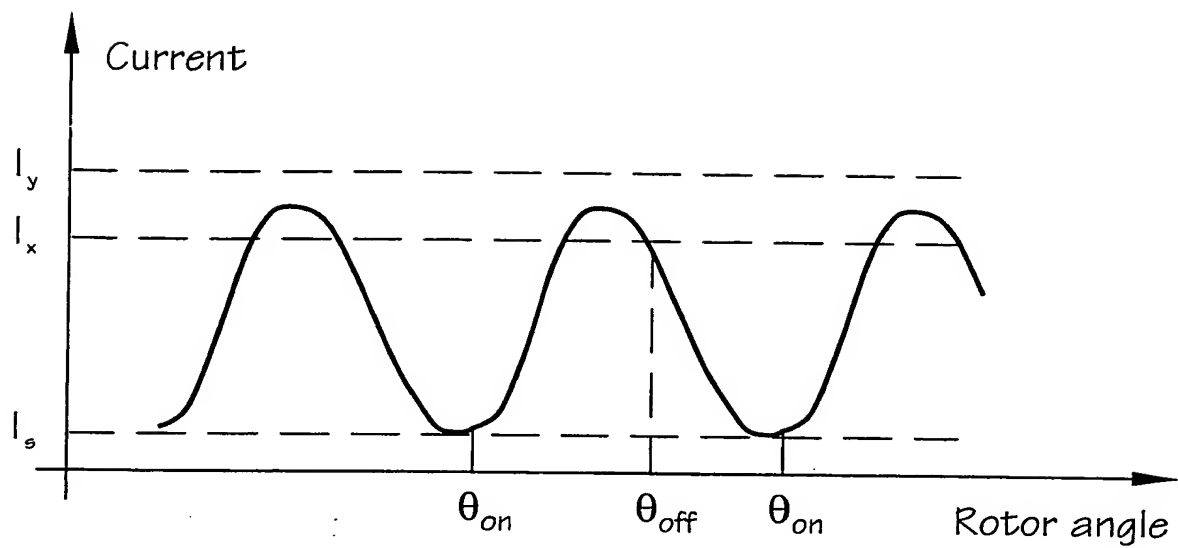


Fig 8

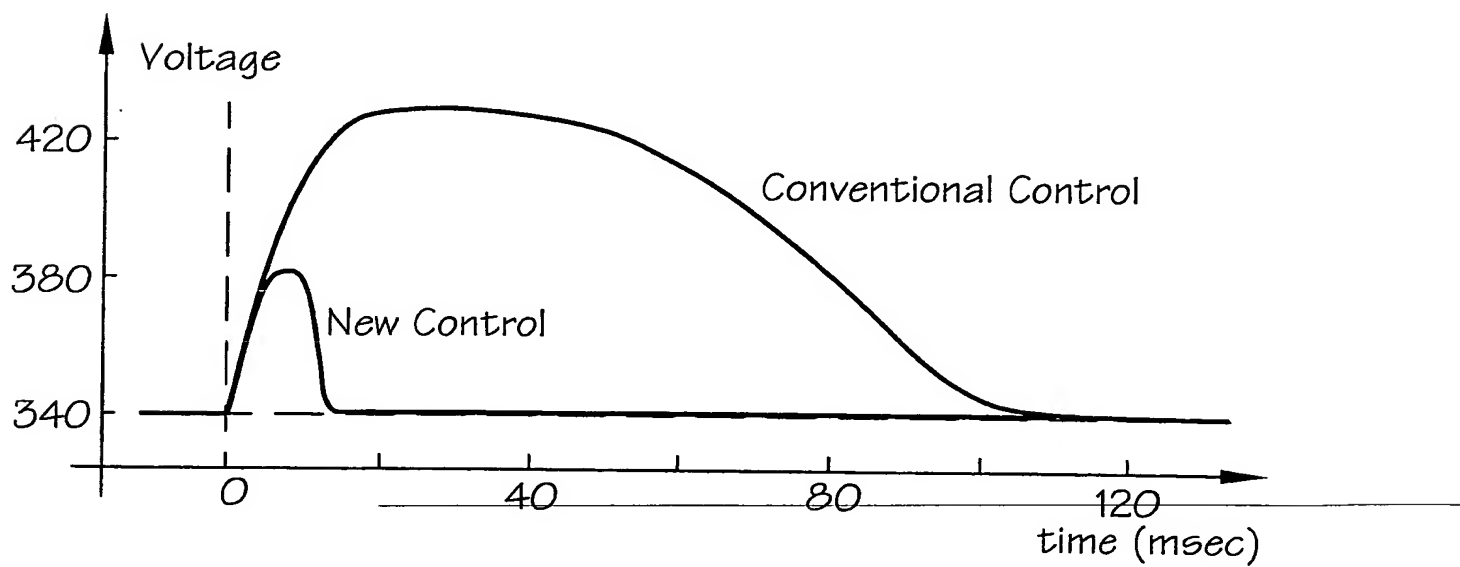


Fig 9